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MECHANICAL PROPERTIES OF TITANIUM AND ALUMINUM ALLOYS AT CRYOGENIC TEMPERATURES

TECHNICAL REPORT WAL TR 340.2/1

BY

CHARLES F. HICKEY, Jr.

DATE OF ISSUE - MARCH 1962

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INDUSTRIAL PREPAREDNESS MEASURE - PRODUCT IMPROVEMENT

WATERTOWN ARSENAL
WATERTOWN 72, MASS.

AD

Nonferrous alloys - mechanical properties

Low temperature

Titanium alloys

Aluminum alloys

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TITLE

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ABSTRACT

Low temperature mechanical properties of titanium and aluminum alloys in both bar and sheet form were obtained as a function of testing temperature. For bar material tensile and Charpy impact data were obtained at temperatures ranging from room temperature to -452 F for the tensile and from room temperature to -441 F for the Charpy tests. For the material in the sheet form, notched tension sheet and unnotched tension sheet data were obtained at temperatures between room temperature and -320 F. A unique aspect of this work is the fact that materials which were investigated in both the bar and sheet form were from the same heat.

The results of this investigation indicate that a majority of the titanium and nearly all the aluminum alloys are acceptable for applications in a cryogenic environment.

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REPORT APPROVED
Date 25 May 1962
WAL Board of Review
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APPROVED:

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Director
Watertown Arsenal Laboratories

CONTENTS

INTRODUCTION

With the current and ever-increasing interest in high strength and thin gage materials for missiles, rockets, aircraft, and component applications in a low-temperature environment, the mechanical properties of such materials have become of tremendous importance. Since a prime criterion used for selecting materials for such applications is the strength/weight ratio, titanium and aluminum alloys have been greatly emphasized. For any given strength level, their respective strength/weight ratios are approximately 1.7 and 2.8 times greater than that of steel. In recent years, there have been numerous publications on low-temperature mechanical properties of these materials at temperatures down to -320 F and in many cases as low as -423 F.[1-6] Currently liquid hydrogen, -423 F, is the lowest temperature propellant being utilized, and data at lower temperatures have not been of great necessity. Therefore, little work has been done at temperatures below -423 F. However, in the very near future, data obtained at liquid helium temperature, -452 F, will be necessary in order to design systems which can withstand the lower temperature environment.

This report is a presentation of low-temperature mechanical property data which have been obtained from numerous titanium and aluminum alloys in both bar stock and sheet form. The investigation is unique because materials investigated in both the bar and sheet form are from the same heat.

Tensile and impact properties were obtained at temperatures ranging from room to liquid helium temperatures on the bar materials and tension sheet data from room temperature to -320 F for the sheet materials. The notch tensile ratios were determined on sheet specimens as a function of testing temperature, thus providing a criterion for resistance to brittle fracture.[5]

MATERIALS

The materials selected for this investigation included 7Al-4Mo, 7Al-3Mo, 6Al-4V, 4Al-3Mo-1V, 16V-2.5Al, 13V-11Cr-3Al, 7Al-4V, 6.5Al-3Mo-1V, and 155A for the titanium alloys and 6061-T6, 7075-T6, 2017-T4, 2024-T4, 2014-T6, 2024-T3, Alclad 2024-T3, and 5086-H34 for the aluminum alloys. Table I is a tabulation of the chemical composition of the titanium alloys. The bar was 5/8 inch in diameter and the sheet 0.060 inch in thickness. The nominal chemical composition of the aluminum alloys is presented in Table II. The aluminum bar was 5/8 inch in diameter and the sheet 0.050 inch in thickness.

PROCEDURE

Standard V-notch Charpy impact and 0.252 inch tension specimens were obtained from the bar materials of both the titanium and aluminum alloys. The specimens obtained from the sheet materials of both metals were of a special design and included both unnotched and notched type specimens. Figures 1a and 1b contain sketches of the unnotched and notched tension sheet specimens selected for this program. All notched specimens had a 30 percent notch and a stress concentration factor (K_t) of 11.2 except for the titanium materials tested at -320 F. For testing at this temperature, the specimens were further modified by decreasing the width between the notches in an effort to assure fracture in the notched area. The K_t for this design was 10.0. The notch radius in all cases was 0.002 inch.

The stress concentration factors were calculated by means of the following equation:

$$K_t = \sqrt{\frac{\text{1/2 width between notches}}{\text{radius of notch}}}$$

Titanium and aluminum 0.252-inch tension specimens were tested on a 60,000-pound capacity Universal hydraulic machine. A strain rate of 0.005 inch per minute up to 0.2 percent offset followed by a platen displacement of 0.02 inch per minute to fracture was used for titanium bar materials tested between room temperature and -320 F. For aluminum bars and also for titanium bars tested at -452 F a constant platen displacement of 0.01 inch per minute was used. All tensile testing below -320 F was conducted in a tensile cryostat.[6]

Sheet specimen testing for both alloy materials was performed on a 30,000-pound capacity Tinius Olsen hydraulic machine, using the same testing procedure as for bar form.

V-notch Charpy impact specimens were tested on a 240 ft-lb Sonntag machine for temperatures down to -320 F. An impact cryostat[7] was used for obtaining Charpy values at -441 F.

All titanium alloys were tested in the mill-annealed condition.

RESULTS AND DISCUSSION

Titanium Alloys

A tabulation of the titanium test data is presented in Tables III and IV, and curves representing the mechanical properties of each alloy are shown in Appendix A.

Ti-7Al-4Mo

Strength values for this titanium alloy, as shown in Figure A-1, increase over the decreasing temperature span except for the notch strength,

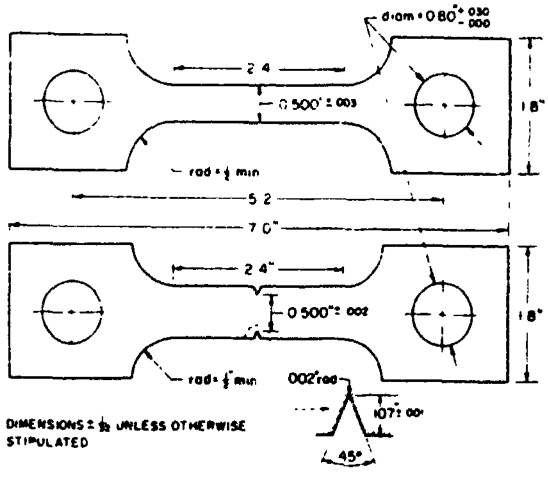


FIGURE 1a

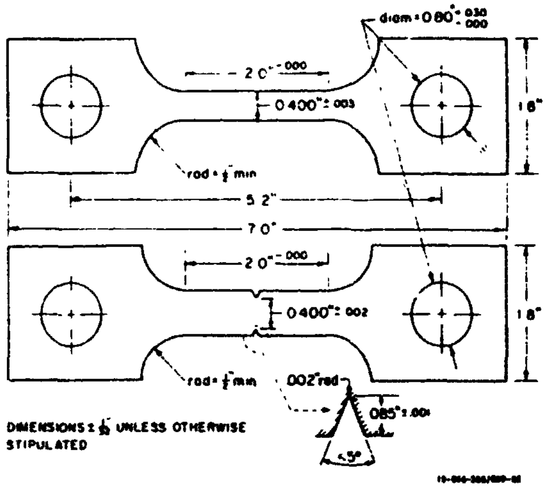


FIGURE 1b

NOTCHED AND UNNOTCHED TENSION SHEET SPECIMEN DESIGN

indicating that the material is notch sensitive, especially at the lower temperatures. (A plot of notch tensile ratio as a function of testing temperatures for all titanium materials is shown in Figure A-8). Bar and sheet (unnotched specimen) strength data are similar; however, bar elongation values are consistently higher than sheet. V-notch Charpy impact values decreased from 16 ft-lb at +212 F to 10.8 ft-lb at -441 F.

Ti-7Al-3Mo

Figure A-2 is a plot of the mechanical properties of Ti-7Al-3Mo. Tensile strength values increased at approximately the same rate as yield values as testing temperature decreased. Notched values decreased as a function of testing temperature, thus indicating notch sensitivity. For the most part, ductility is only slightly sensitive to a low-temperature environment, even at -452 F. Impact values decreased from 11.8 to 6.4 ft-lb over the temperature range investigated.

Ti-6Al-4V

Tensile and yield strength data for both bar and sheet of this titanium alloy are shown in Figure A-3. Bar and sheet data show approximately the same increase in strength as testing temperature is decreased and except for the data at -240 F, where the bar values are higher, there is little difference between bar and sheet data. Results from notched specimens show that the material is not notch sensitive down to -240 F. The respective notch tensile ratio values at -240 and -320 F are 0.92 and 0.78. It is noteworthy to mention that reduction of area values ranged from 52 percent at room temperature to 32 percent at -452 F. Elongation values of the material in bar form are somewhat higher than those of the material in sheet form and this property is temperature sensitive below -320 F. Impact properties are temperature sensitive; however, this alloy still exhibits a value of 13.8 ft-lb at -441 F.

Ti-4Al-3Mo-1V

Figure A-4 is a plot of the mechanical properties of Ti-4Al-3Mo-1V. It is apparent that the tensile and yield strength data show a large increase as testing temperature is decreased with the data from the bar material being higher than the data from the unnotched sheet specimens. Notched strength values are higher than unnotched results at all temperatures, thus indicating that this material is not notch sensitive. Reduction of area values range from 62 percent at room temperature to 35 percent at -452 F. Elongation is rather insensitive to a decreasing temperature environment, dropping gradually from 20 percent at room temperature to 15 percent at -320 F and then sharply to 9 percent at -452 F. In general, elongation values of sheet material are slightly higher than those of bar material. Impact values for this material are very high, but they decrease rapidly as temperature decreases to -320 F. The value of 17.1 ft-lb at -320 F does not change appreciably at -441 F, thus this material exhibits good impact properties at ultra low temperatures.

Ti-16V-2.5Al

Mechanical properties versus testing temperature for Ti-16V-2.5Al are shown in Figure A-5. With the exception of room temperature properties, the strength of the bar material was consistently higher than the strength of the sheet material down to -240 F. Bar material data below -240 F could not be obtained since specimens tested at -320 F broke before the desired offset was reached. The notch tensile ratio for this material is extremely sensitive to a temperature environment below -105 F. The ratio at -105 F is 0.96 and it drops to 0.58 at -320 F. Ductility values indicated that bar material is sensitive to the temperature environment below -105 F. The impact properties of this material are low at all temperatures.

Ti-13V-11Cr-3Al

Data on Ti-13V-11Cr-3Al are presented in Figure A-6. Mechanical properties of this alloy are extremely sensitive to a decrease in testing temperature. Strength values are similar for the material in both bar and sheet forms except for the notch tensile properties which are somewhat higher down to -105 F and thereafter decrease drastically at the lower temperatures. The notch tensile ratio ranges from a maximum of 1.12 at room temperature to a low of 0.33 at -320 F.

Ti-7Al-4V, 6.5Al-3Mo-1V, and 155A

Figure A-7 contains data obtained from Ti-7Al-4V, Ti-6.5Al-3Mo-1V, and Ti-155A alloys in bar form. The tensile strength for the materials increased uniformly over the temperature range investigated. Ductility and impact values for Ti-7Al-4V and Ti-6.5Al-3Mo-1V were superior to those of Ti-155A at -240 F and below.

Notched Tensile Ratio

Figure A-8 is a plot of the notch tensile ratio as a function of testing temperature (room temperature to -320 F) for the titanium sheet materials described in Figures A-1 to A-7. The Ti-4Al-3Mo-1V is both notch and temperature insensitive. All notch tensile ratios for this material lie between 1.09 and 1.18. Notch tensile properties for the remainder of the alloys are temperature sensitive. The Ti-13V-11Cr-3Al material showed the greatest notch tensile ratio decrease, being 1.12 at room temperature and dropping to 0.33 at -320 F. Room temperature values were 1.0 or greater for all alloys except for Ti-7Al-3Mo and Ti-7Al-4Mo. These two materials each had a value of 0.91.

Aluminum Alloys

A tabulation of the aluminum test data is presented in Tables V and VI and curves representing the mechanical properties of each alloy are shown in Appendix B.

6061-T6

Figure B-1 is a plot of the mechanical properties for aluminum alloy 6061-T6 in both the bar and sheet form. Data on the material in bar form showed a marked increase in tensile strength at -452 F without a loss in ductility. Impact values were insensitive to the low temperature environment. Notch tensile ratio values ranged from 1.06 at room temperature to 0.93 at -320 F. A plot of notch tensile ratio as a function of testing temperature for the aluminum alloys is shown in Figure B-6.

7075-T6

Figure B-2 shows results from 7075-T6 in both bar and sheet form. Tensile strength values of the bar material increased from 82,000 psi at room temperature to 116,000 psi at -452 F. Ductility and impact decrease slightly over the low temperature range. Data on the sheet material point out that this material is notch sensitive. It has a room temperature value of 0.89 which decreases to 0.67 at -320 F.

2024-T4 and 2017-T4

The effect of cryogenic testing temperatures on the mechanical properties of 2024-T4 and 2017-T4 in bar form are shown in Figure B-3.

Tensile and yield strengths increased approximately 40,000 psi over the temperature range investigated, with the major environmental effect occurring between -320 and -452 F. Ductility and impact showed no appreciable decrease as the temperature decreased.

2024-T3 and Alclad 2024-T3

Figure B-4 is a plot of data obtained from notched and unnotched sheet specimens of 2024-T3 and Alclad 2024-T3. Strength properties showed a gradual increase while elongation values decreased over the low temperature range down to -320 F. Room temperature notch tensile ratios are between 0.8 and 1.0 for both alloys and these values change little due to testing temperature.

2014-T6 and 5086-H34

Data from notched and unnotched sheet specimens of 2014-T6 and 5086-H34 are shown in Figure B-5. Strength properties of both materials plus elongation values for 5086-H34 tend to increase with a decrease in testing temperature. The room temperature notch tensile ratio for the materials is in the order of 0.9 and this value is altered very little at the lower temperatures.

Notched Tensile Ratio

Figure B-6 is a plot of the notch tensile ratio for the aluminum sheet materials as a function of testing temperature (room temperature to -320 F). The alloy 6061-T6 tends to exhibit the most favorable ratio, having a room temperature value of 1.00 which decreases to only 0.93 at -320 F. The 7075-T6 material was found to be the most notch sensitive of the alloys investigated. Its room temperature value of 0.89 was slightly higher than two other alloys; however, this value decreased with temperature to a ratio of 0.67 at -320 F.

SUMMARY

Titanium

A summary of yield strength and impact values versus testing temperature is shown in Figures 2 and 3 respectively. As indicated in Table III, tensile specimens for Ti-16V-2.5Al and Ti-13V-11Cr-3Al broke in a brittle manner prior to yielding at -320 F, therefore, these materials are not recommended for low temperature applications. The remainder of the titanium alloys were tested from room temperature to -452 F. In general, Ti-7Al-4Mo and Ti-7Al-3Mo had the highest strength properties at the respective testing temperatures, while Ti-4Al-3Mo-1V exhibited the lowest strength properties.

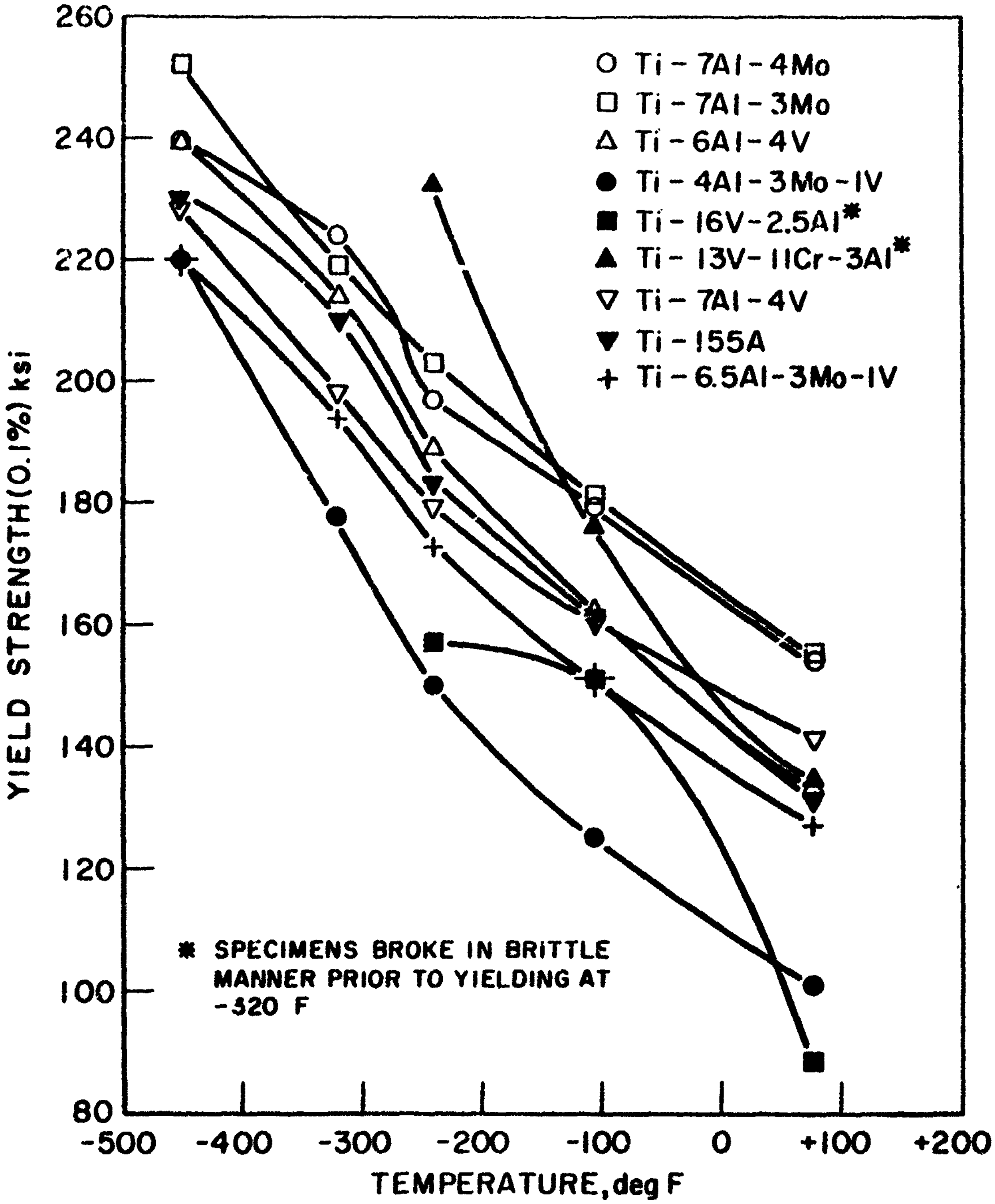
A summary plot is not shown for ductility. In general, however, these properties fared quite well at -452 F. Exceptions to this are elongation values for Ti-6Al-4V and Ti-4Al-3Mo-1V and reduction of area for Ti-155A. Reduction of area values also decreased for Ti-6Al-4V and Ti-4Al-3Mo-1V, however; they were still reasonably high.

Impact properties were very encouraging at -441 F. The Ti-155A and Ti-6.5Al-3Mo-1V alloys were the only materials to decrease appreciably between -320 and -441 F. The titanium alloys 4Al-3Mo-1V and 6Al-4V showed the highest properties over the testing range; 16V-2.5Al and 13V-11Cr-3Al were the lowest.

Based upon a tensile impact criterion, utilization of the following alloys is advocated for a liquid helium environment: Ti-7Al-4Mo, Ti-7Al-3Mo, Ti-6Al-4V, Ti-4Al-3Mo-1V, Ti-7Al-4V, and Ti-6.5Al-3Mo-1V.

Figure 4 is a plot of notch tensile ratio versus unnotched tensile strength as a function of testing temperature. Such a plot is most informative because the tensile strength per notch tensile ratio as a function of testing temperature can also be depicted. This is of major value for in many design applications the engineer must select an optimum notch tensile ratio and strength combination.

An examination of Figure 4 shows that Ti-4Al-3Mo-1V has a high notch tensile ratio even at -320 F; however, its strength range is limited. In general, the remaining alloys exhibit a fairly uniform decrease in notch tensile ratio and an increase in tensile strength as the testing temperature is decreased. An exception is Ti-13V-11Cr-3Al which decreases only slightly in notch tensile ratio between room temperature and -105 F, then



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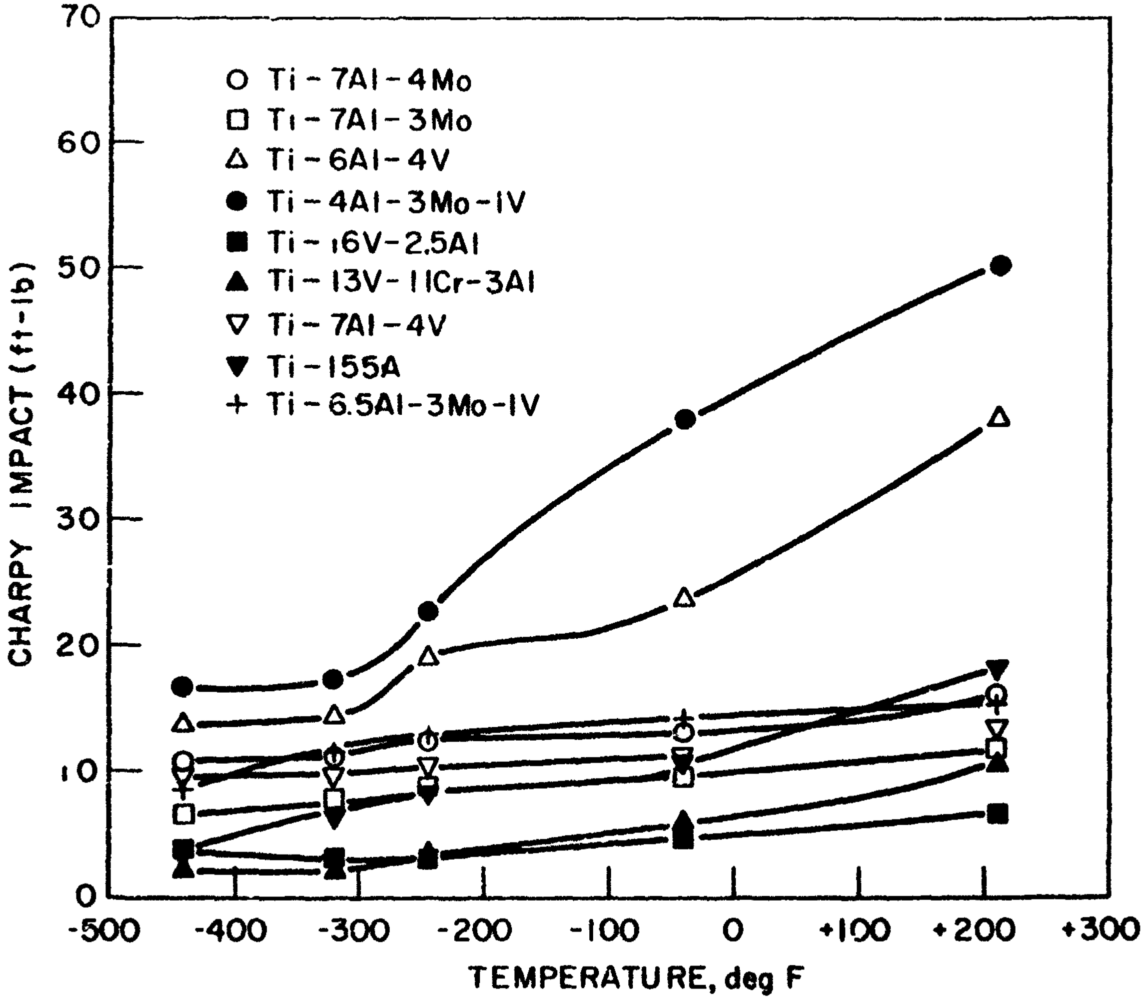
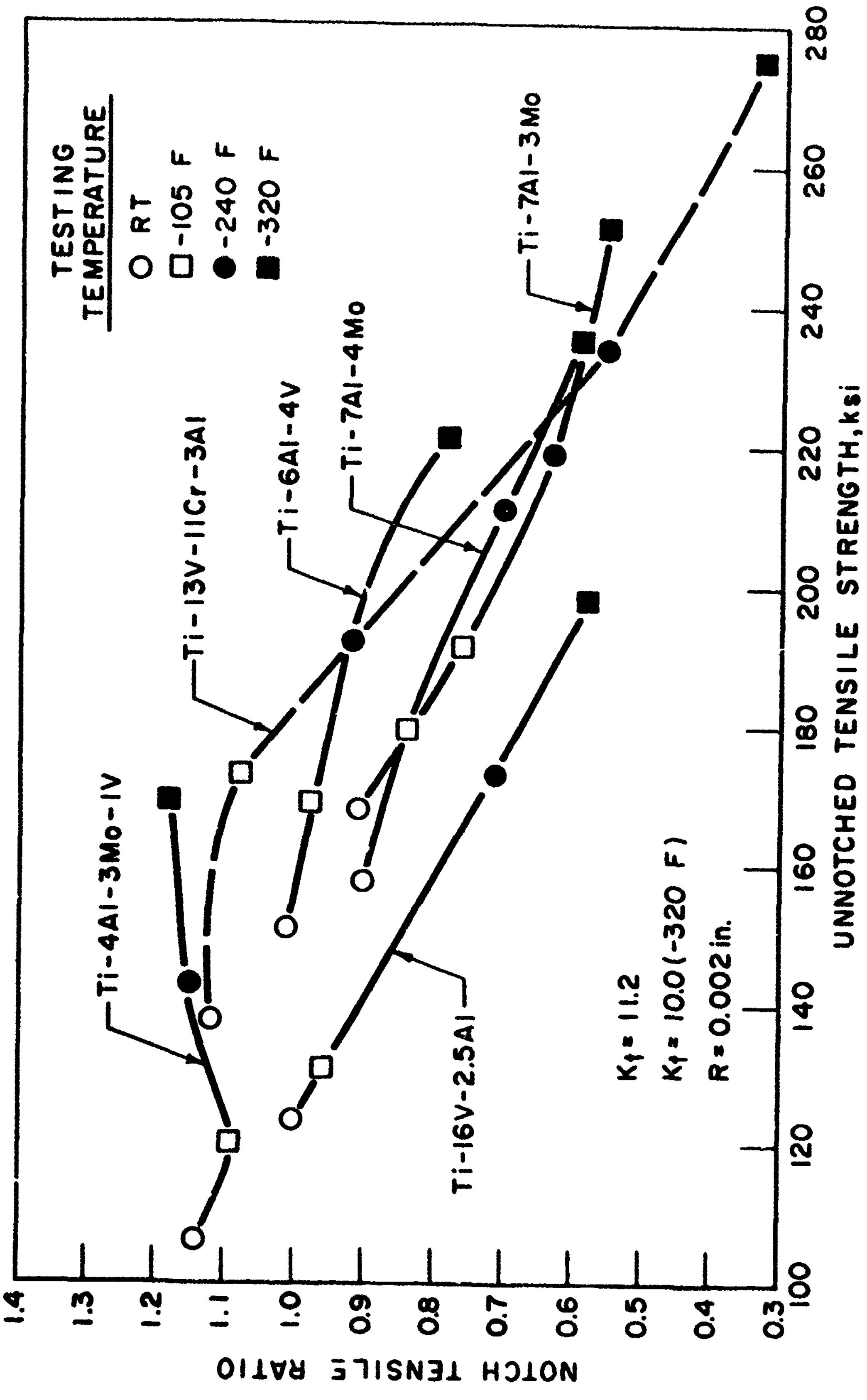
EFFECT OF TESTING TEMPERATURE ON THE YIELD STRENGTH OF TITANIUM ALLOYS

FIGURE 2



EFFECT OF TESTING TEMPERATURE ON THE IMPACT PROPERTIES OF TITANIUM ALLOYS

FIGURE 3



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EFFECT OF TESTING TEMPERATURE ON THE NOTCH TENSILE CHARACTERISTICS OF TITANIUM ALLOYS

FIGURE 4

drastically at -240 F. This is characteristic of this alloy for it undergoes a ductile to brittle transition between -105 and -240 F.

Aluminum

Tensile data were obtained from room temperature to -452 F and impact data from room temperature to -441 F for 6061-T6, 7075-T6, 2024-T6, and 2017-T4 aluminum alloys in the bar form. A summary plot of these data is shown in Figures 5a and 5b. Yield strength values increase and impact values decrease only slightly with the decreased temperature environment. Ductility values are not summarized; however, the results indicated that there is no appreciable loss in ductility at the low temperatures. Thus, it can be stated that these alloys may be considered for usage in a liquid helium environment.

Figure 6 is a plot of notch tensile ratio versus unnotched tensile strength for the aluminum sheet alloys. It is noted that 6061-T6 has the highest notch tensile ratio; however, it is also lowest in tensile strength. In general, the data show an increase in tensile strength and decrease in notch tensile ratio with decreased testing temperature. Exceptions are 2024-T3 and Alclad 2024-T3, which show a slight increase in notch tensile ratio with decreased testing temperature.

The value of the notch tensile test as a criterion of toughness is evidenced for 7075-T6. As mentioned earlier, based upon a tensile impact criterion, this material appeared acceptable for low temperature applications in the bar form. However, in sheet form it can be seen that it is notch sensitive as the testing temperature is decreased. Thus, it appears that in the sheet form 7075-T6 would not be suitable for low temperature applications unless it would be desirable to sacrifice toughness for increased strength.

Bar Versus Sheet Data

In general, strength properties were higher for bar than for sheet material of the same heat. For titanium this difference ranged from a minimum of approximately 3,000 to 5,000 psi in the 6Al-4V and 13V-11Cr-3Al alloy to a maximum of 28,000 psi for Ti-16V-2.5Al. The two aluminum alloys of the same heat were approximately 3,000 psi higher in the bar form.

An exception to the general trend is Ti-7Al-3Mo. In this material the sheet values are higher at all temperatures by an average of 7,000 psi.

A possible explanation for the variance in bar and sheet data, especially in titanium, may lie in the fact that each form received a different type and amount of working, thus giving rise to a different structure and texture.

It should also be recognized that due to the difference in specimen geometry, one can not justifiably compare bar and sheet values. However, trendwise, it can be stated that in general the bar values are slightly superior to those obtained from the sheet.

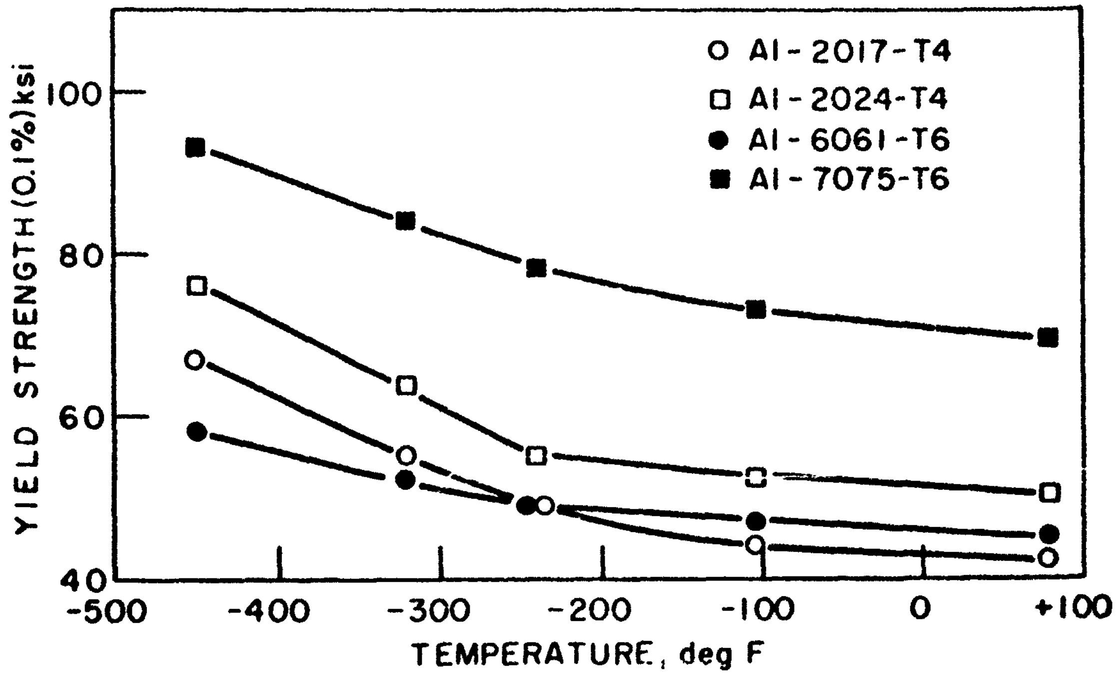

FIGURE 5a: EFFECT OF TESTING TEMPERATURE ON THE YIELD STRENGTH OF ALUMINUM ALLOYS

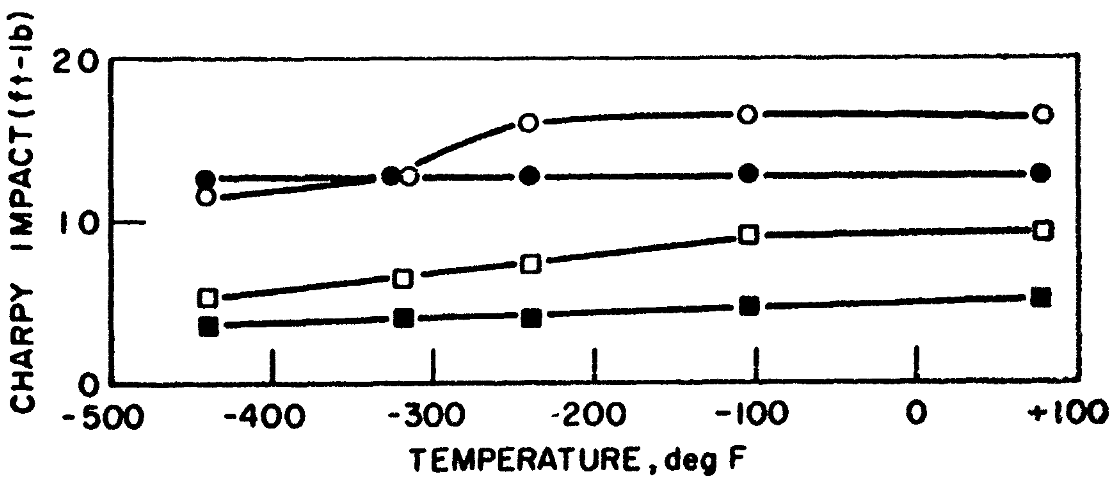

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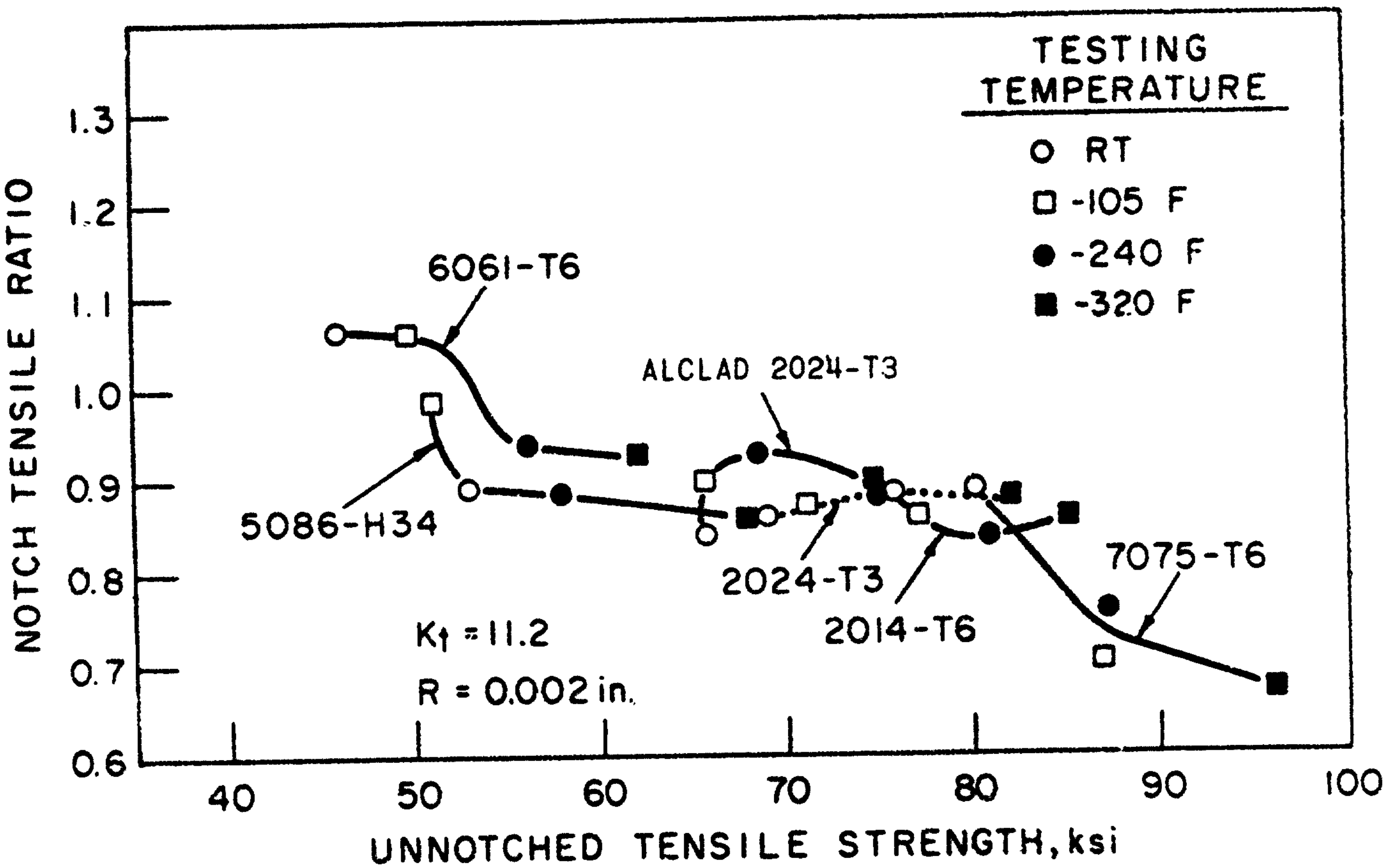
FIGURE 5b: EFFECT OF TESTING TEMPERATURE ON THE IMPACT PROPERTIES OF ALUMINUM ALLOYS



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EFFECT OF TESTING TEMPERATURE ON THE NOTCH TENSILE CHARACTERISTICS OF ALUMINUM ALLOYS

FIGURE 6

TABLE I

HISTORY AND CHEMICAL ANALYSIS OF TITANIUM ALLOYS

Ti Alloy	Heat	C	N	Al	V	Mo	Cr	O_2	H_2
7Al-4Mo	X 70004	0.065	0.007	7.16	-	4.19	-	0.080	0.0036
7Al-3Mo	1 129-S	0.036	0.014	7.03	-	2.70	-	0.094	0.0110
6Al-4V	R 11883	0.025	0.008	5.84	4.23	-	-	0.071	0.0050
4Al-3Mo-1V	X 70006	0.045	0.009	3.85	0.96	3.07	-	0.060	0.0024
16V-2.5Al	X 70002	0.025	0.025	2.79	15.80	-	-	0.080	0.0018
13V-11Cr-3Al	X 70003	0.028	0.013	3.10	13.18	-	10.96	0.060	0.0069

NOTE: All alloys listed were received in bar and sheet form.

Alloys 7Al-4V, 6.5Al-3Mo-1V, and 155A were received in bar form only. Analyses for these alloys are not available.

Bar Diameter 5/8 inch

Sheet Thickness 0.060 inch

Condition - Mill annealed

TABLE II

HISTORY AND NOMINAL CHEMISTRY COMPOSITION OF ALUMINUM ALLOYS

Al Alloys	Form	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
6061-T6	Bar and Sheet	0.40 to 0.80	0.70	0.15 to 0.40	0.15	0.80 to 0.35	0.15 to 1.20	0.25	0.15
7075-T6	Bar and Sheet	0.50	0.70	1.20 to 2.00	0.30	2.10 to 2.90	0.18 to 0.40	5.10 to 6.10	0.20
2017-T4	Bar	0.80	1.00	3.50 to 4.50	0.40 to 1.00	0.20 to 0.80	0.10	0.25	-
2024-T4	Bar	0.50	0.50	3.80 to 4.90	0.30 to 0.90	1.20 to 1.80	0.10	0.25	-
2014-T6	Sheet	0.50 to 1.20	1.00	3.90 to 5.00	0.40 to 1.20	0.20 to 0.80	0.10	0.25	0.15
2024-T3	Sheet	0.50	0.50	3.80 to 4.90	0.30 to 0.90	1.20 to 1.80	0.10	0.25	-
Alclad 2024-T3	Sheet	0.50	0.50	3.80 to 4.90	0.30 to 0.90	1.20 to 1.80	0.10	0.25	-
5086-H34	Sheet	0.40	0.60	0.10	0.80	0.80 to 1.50	0.35	0.20	0.10

Bar Diameter 5/8 inch

Sheet Thickness 0.050 inch

TABLE III

LOW-TEMPERATURE MECHANICAL PROPERTIES OF TITANIUM ALLOYS IN 5/8-INCH DIAMETER BAR STOCK

Titanium Alloy	Temperature (deg F)	Yield Strength (0.1%) (ksi)	Tensile Strength (ksi)	Elongation (%)	Reduction of Area (%)	Impact (ft-lb)
7Al-4Mo	RT	154	160	13	38	16.0[a]
	-105	180	188	13	31	13.1[b]
	-240	197	208	14	32	12.5
	-320	224	241	10	26	11.2
	-452	240	262	6	26	10.8[c]
7Al-3Mo	RT	155	161	14	30	11.8[a]
	-105	181	186	12	24	9.8[b]
	-240	203	214	10	25	8.5
	-320	219	240	9	25	7.9
	-452	252	262	9	21	6.4[c]
6Al-4V	RT	133	143	14	52	38.0[a]
	-105	162	171	12	43	23.6[b]
	-240	189	198	12	45	19.0
	-320	214	221	11	43	14.4
	-452	240	248	4	32	13.8[c]
4Al-3Mo-1V	RT	100	117	20	62	50.3[a]
	-105	125	141	17	53	38.0[b]
	-240	150	166	17	51	22.5
	-320	178	200	15	46	17.1
	-452	220	226	9	35	16.4[c]
16V-2.5Al	RT	88	129	10	23	6.5[a]
	-105	151	182	9	20	4.7[b]
	-240	157	202	2.5	3.4	3.5
	-320	d	d	-	-	3.0
	-452	-	-	-	-	3.6[c]
13V-11Cr-3Al	RT	134	136	21	34	10.5[a]
	-105	176	181	10	22	5.6[b]
	-240	232	239	2	3.4	3.3
	-320	d	d	-	-	2.2
	-452	-	-	-	-	2.3[c]
7Al-4V	RT	141	157	12.8	42	13.6[a]
	-105	161	184	11	34	11.2[b]
	-240	179	207	12	32	10.3
	-320	198	235	13	26	9.6
	-452	228	247	9	29	9.5[c]

TABLE III (Cont)

LOW-TEMPERATURE MECHANICAL PROPERTIES OF TITANIUM ALLOYS IN 5/8-INCH DIAMETER BAR STOCK

Titanium Alloy	Temperature (deg F)	Yield Strength (0.1%) (ksi)	Tensile Strength (ksi)	Elongation (%)	Reduction of Area (%)	Impact (ft-lb)
0.5Al-3Mo-1V	RT	127	149	16	51	15.5[a]
	-105	151	173	16	46	14.1[b]
	-240	173	205	18	44	13.0
	-320	194	233	12	39	11.6
	-452	220	252	11	36	8.5[c]
Ti-155A	RT	131	139	17	39	18.1[a]
	-105	162	172	14	33	10.5[b]
	-240	183	203	11	25.3	8.6
	-320	210	235	7	18	6.4
	-452	230	248	4	9	3.5[c]

a Testing Temperature +212 F
b Testing Temperature -40 F
c Testing Temperature -441 F
d Specimen broke in brittle manner prior to yielding

TABLE IV

LOW-TEMPERATURE MECHANICAL PROPERTIES OF TITANIUM SHEET MATERIALS IN SHEET THICKNESS OF 0.060 INCH

Titanium Alloy	Temperature (deg F)	Unnotched Yield Strength (0.1%) (ksi)	Unnotched Tensile Strength (ksi)	Unnotched Elongation (%)	Notched Tensile Strength (ksi)	Notched/Unnotched Ratio $K_t = 11.1$
7Al-4Mo	RT	152	158	7.0	143	0.91
	-105	169	179	2.5	151	0.84
	-240	196	211	3.0	148	0.70
	-320	213	235	2.0	139	0.59 [b]
7Al-3Mo	RT	159	168	15.0	153	0.91
	-105	176	191	5.0	146	0.76
	-240	204	219	3.5	139	0.63
	-320	240	251	7.5	138	0.55 [b]
6Al-4V	RT	141	151	13.0	152	1.01
	-105	157	169	2.5	165	0.98
	-240	173	192	8.0	177	0.92
	-320	214	221	7.0	173	0.78 [b]
4Al-3Mo-1V	RT	103	106	20.5	121	1.14
	-105	112	120	20.0	131	1.09
	-240	131	143	14.0	165	1.15
	-320	156	169	22.0	200	1.18 [b]
16V-2.5Al	RT	106	124	8.0	124	1.00
	-105	110	131	5.0	126	0.96
	-240	126	173	a	122	0.71
	-320	176	198	2.0	115	0.58 [b]
13V-11Cr-3Al	RT	131	138	14.0	154	1.12
	-105	165	173	18.0	187	1.08
	-240	225	234	6.5	129	0.55
	-320	262	275	a	91	0.33 [b]

a Multiple Fracture
b $K_t = 10.0$

TABLE V

LOW-TEMPERATURE MECHANICAL PROPERTIES OF ALUMINUM ALLOYS FROM 5/8-INCH DIAMETER BAR STOCK

Alloy	Temperature (deg F)	Yield Strength (0.1%) (ksi)	Tensile Strength (ksi)	Elongation (%)	Reduction of Area (%)	Impact (ft-lb)
2017-T4	RT	42	66	23.6	43.7	16.4
	-105	44	64	26.0	37.8	16.5
	-240	49	74	27.5	32.5	16.0
	-320	55	84	26.0	26.6	12.7
	-452	67	104	24.0	27.1	11.6[a]
2024-T4	RT	50	72	20.0	32.4	9.4
	-105	52	74	20.0	24.3	9.0
	-240	55	78	20.0	22.6	7.4
	-320	64	87	15.0	16.5	6.4
	-452	76	107	20.0	20.8	5.3[a]
6061-T6	RT	45	50	15.3	51.1	12.6
	-105	47	54	16.5	50.4	13.0
	-240	49	59	19.0	45.5	12.9
	-320	52	64	19.0	41.6	12.7
	-452	58	83	22.0	39.2	12.6[a]
7075-T6	RT	69	82	15.8	34.7	5.2
	-105	73	86	14.0	26.0	4.7
	-240	78	92	15.0	24.0	3.9
	-320	84	98	14.0	23.4	4.0
	-452	93	116	19.0	22.7	3.5[a]

a Testing Temperature -441 F

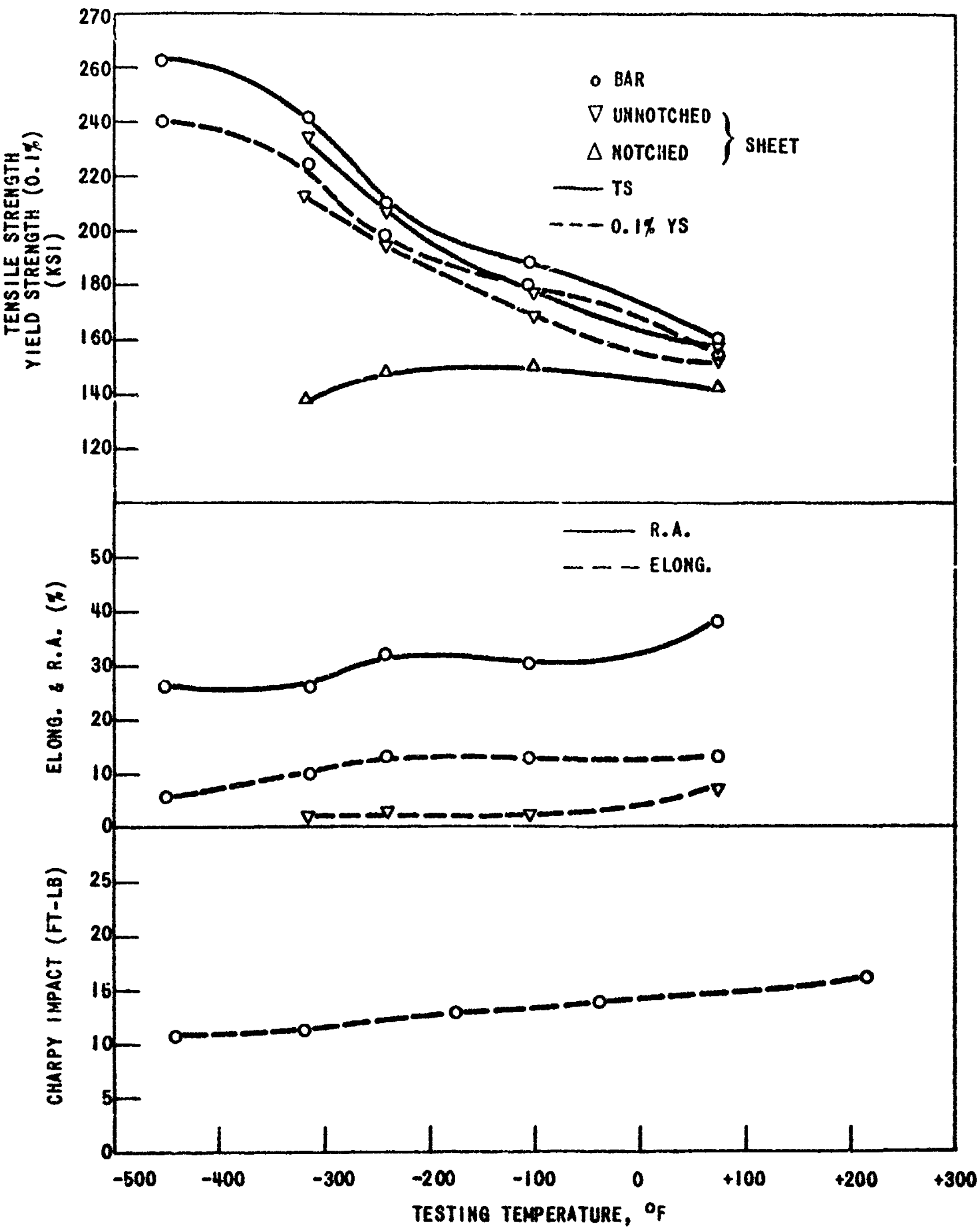
TABLE VI

LOW-TEMPERATURE MECHANICAL PROPERTIES OF ALUMINUM ALLOYS IN SHEET THICKNESS OF 0.050 INCH

Alloy	Temperature (deg F)	Unnotched Yield Strength (0.1%) (ksi)	Unnotched Tensile Strength (ksi)	Unnotched Elongation (%)	Notched Tensile Strength (ksi)	Notched/Unnotched Ratio $K_t = 11.1$
2014-T6	RT	65	76	9.0	68	0.89
	-105	70	77	8.0	67	0.86
	-240	72	81	11.0	68	0.84
	-320	72	85	9.5	73	0.86
2024-T3	RT	44	69	20.0	60	0.86
	-105	45	71	13.0	62	0.87
	-240	50	75	11.5	67	0.89
	-320	54	82	11.0	73	0.89
Alclad 2024-T3	RT	44	66	19.0	55	0.84
	-105	49	65	13.0	59	0.90
	-240	55	69	9.5	64	0.93
	-320	61	75	10.5	67	0.90
6061-T6	RT	34	46	9.5	48	1.06
	-105	44	50	14.0	52	1.05
	-240	47	56	14.0	53	0.94
	-320	48	62	20.0	57	0.93
7075-T6	RT	68	80	9.5	71	0.89
	-105	77	87	7.0	61	0.70
	-240	76	88	10.0	66	0.76
	-320	81	96	8.0	64	0.67
5086-H34	RT	36	53	8.0	47	0.89
	-105	39	51	8.0	51	0.99
	-240	43	58	13.0	52	0.89
	-320	44	68	22.0	59	0.86

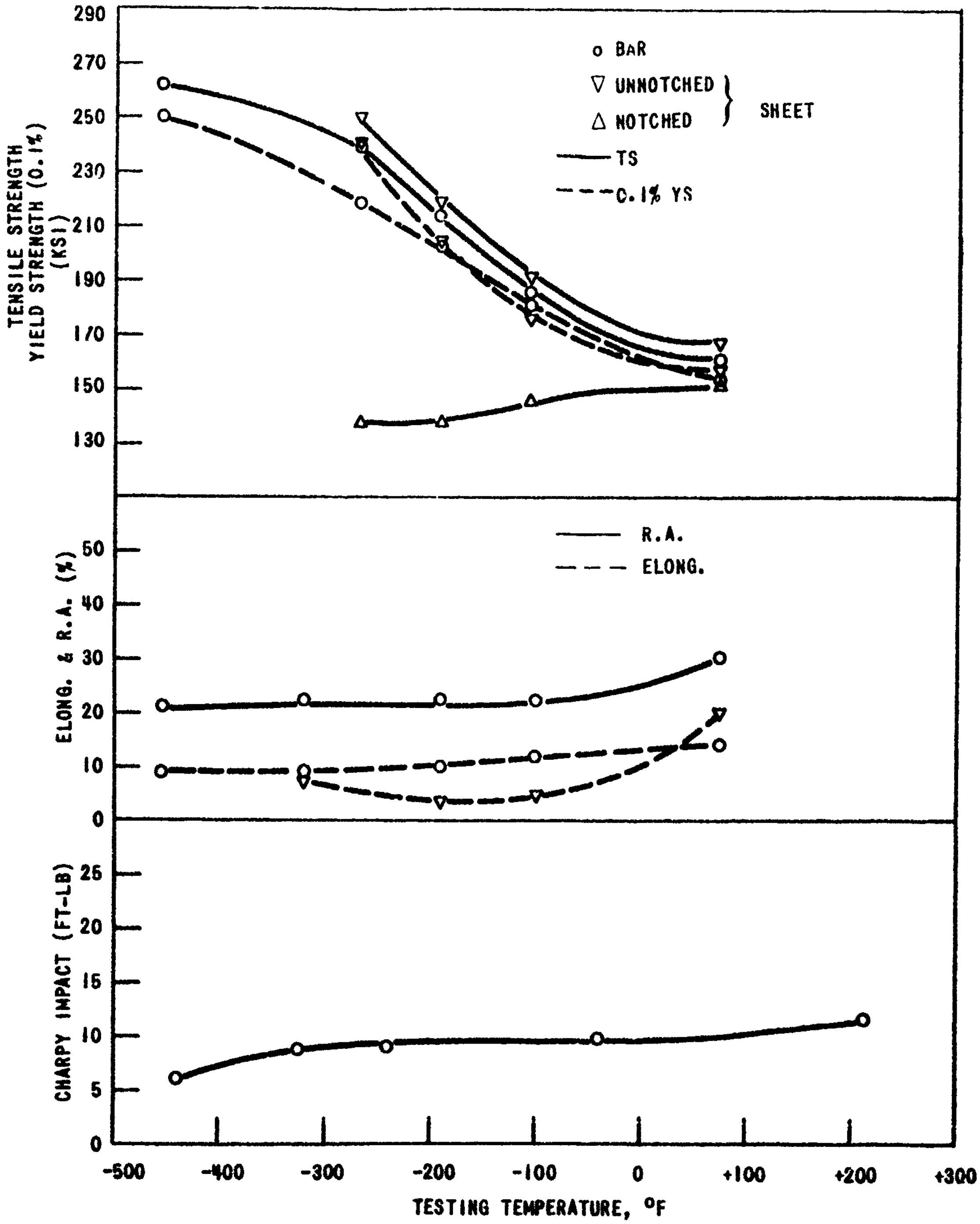
APPENDIX A

MECHANICAL PROPERTY CURVES FOR TITANIUM ALLOYS



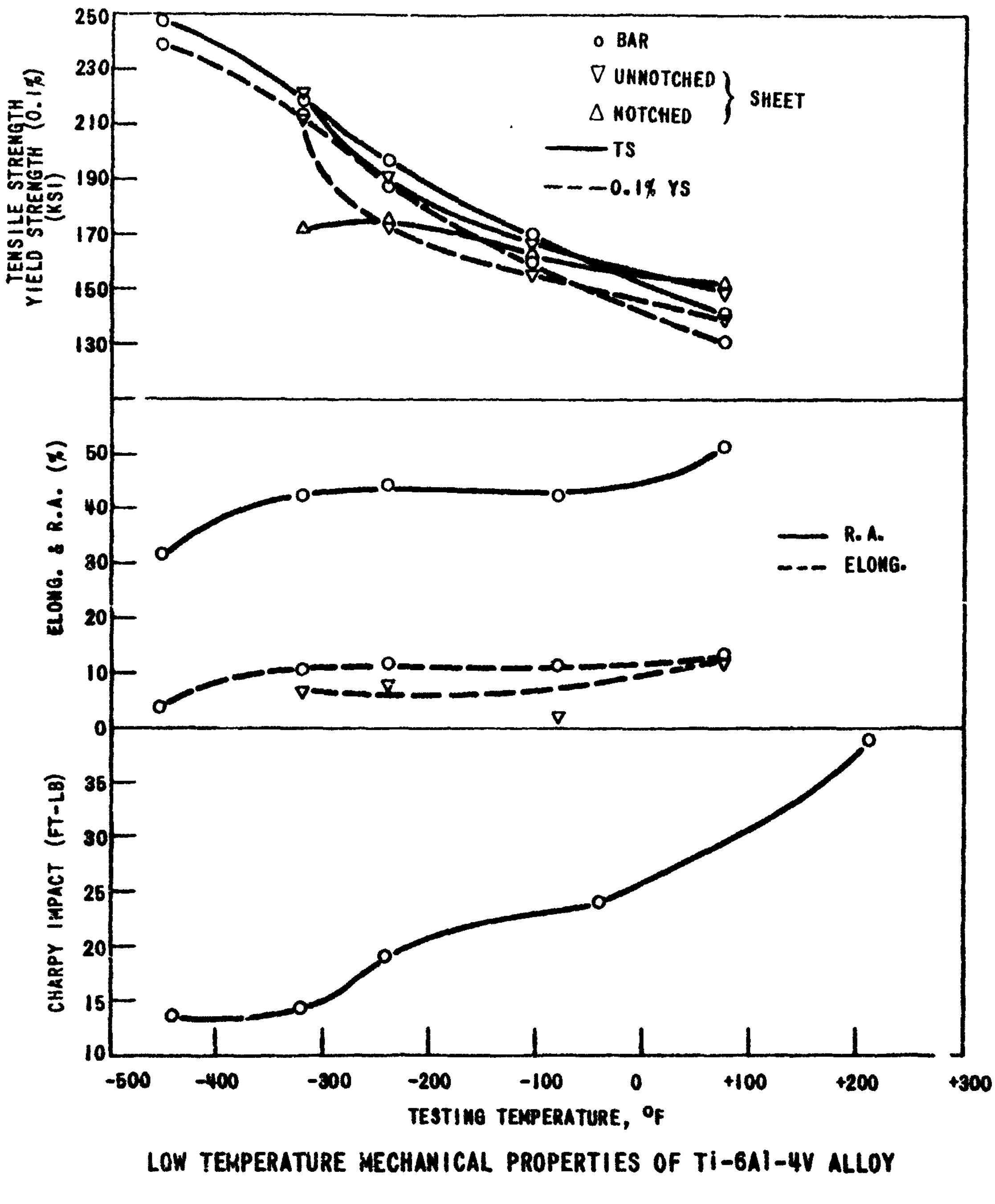
LOW TEMPERATURE MECHANICAL PROPERTIES OF Ti-7Al-4Mo ALLOY

FIGURE A-1



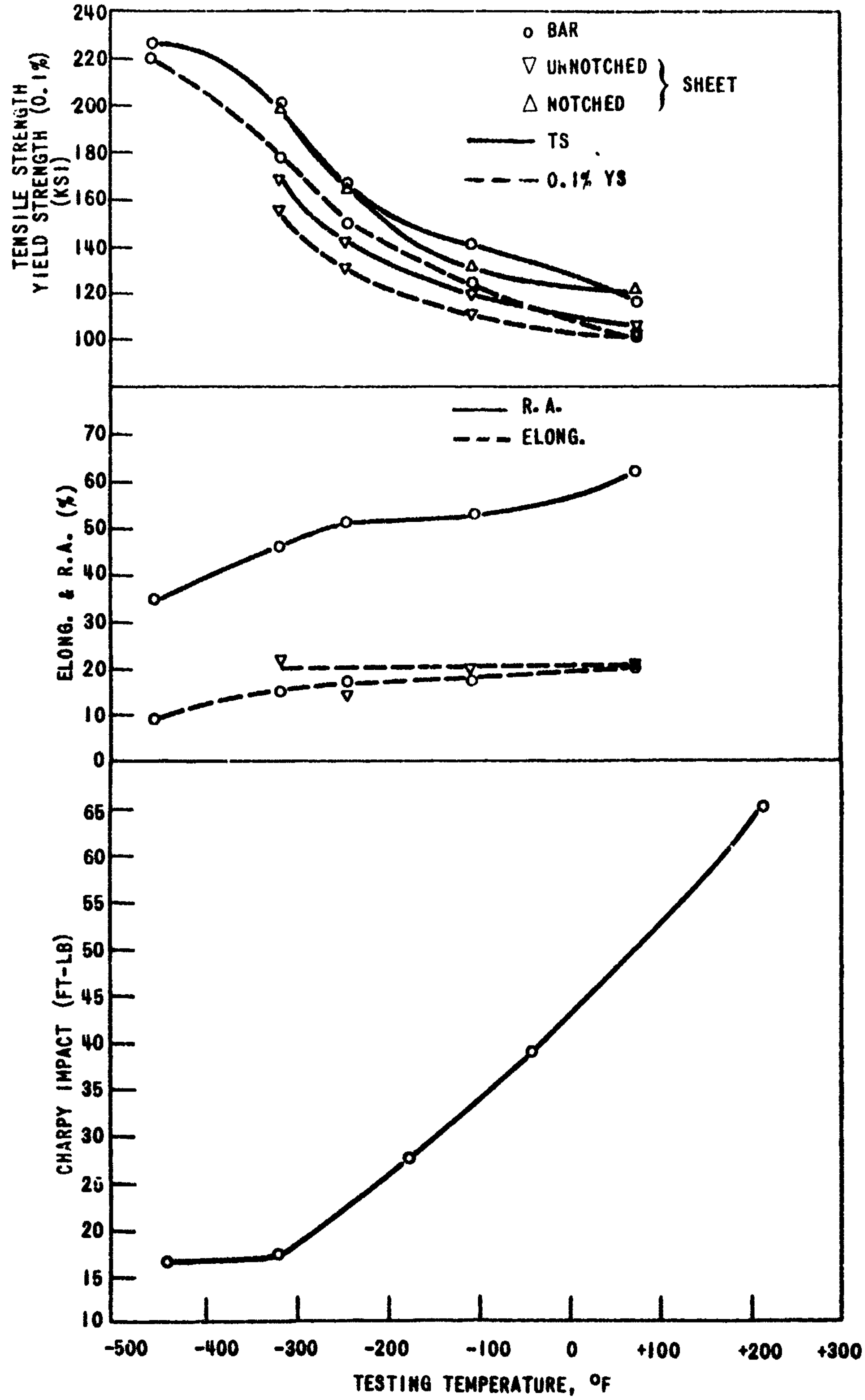
LOW TEMPERATURE MECHANICAL PROPERTIES OF Ti-7Al-3Mo ALLOY

FIGURE A-2



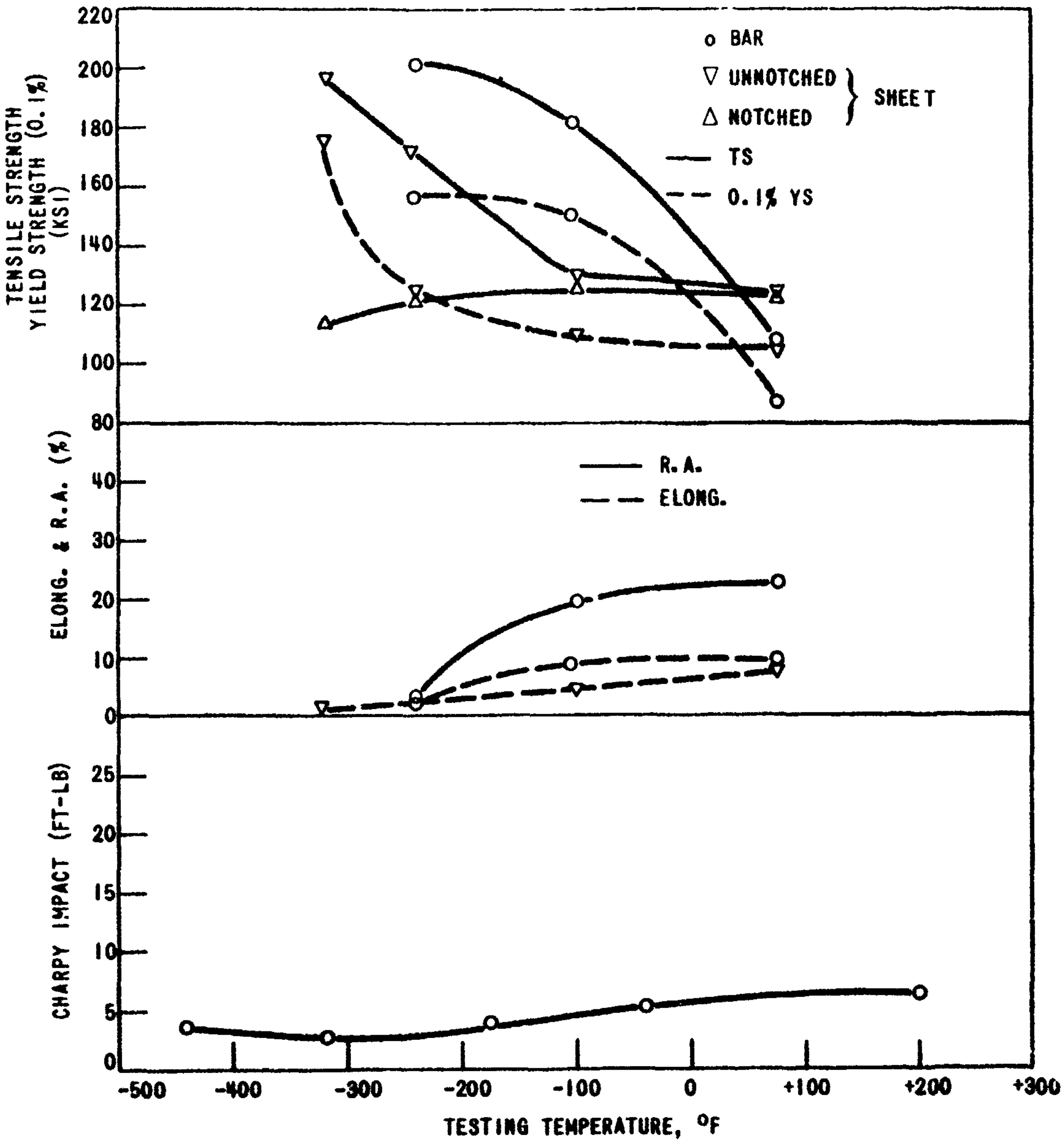
LOW TEMPERATURE MECHANICAL PROPERTIES OF Ti-6Al-4V ALLOY

FIGURE A-3



LOW TEMPERATURE MECHANICAL PROPERTIES OF Ti-4Al-3Mo-1V ALLOY

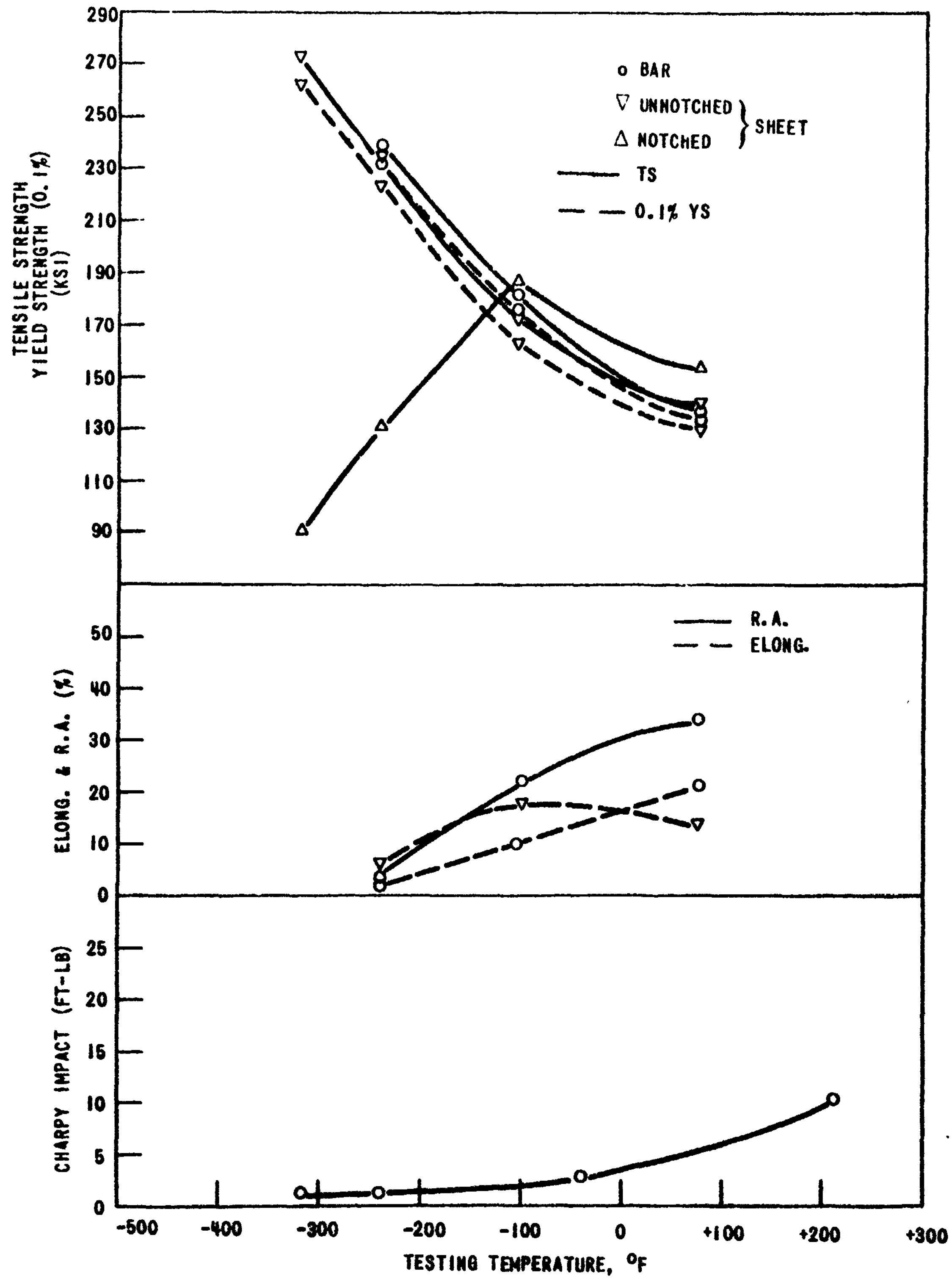
FIGURE A-4



LOW TEMPERATURE MECHANICAL PROPERTIES OF Ti-16V-2.5Al ALLOY

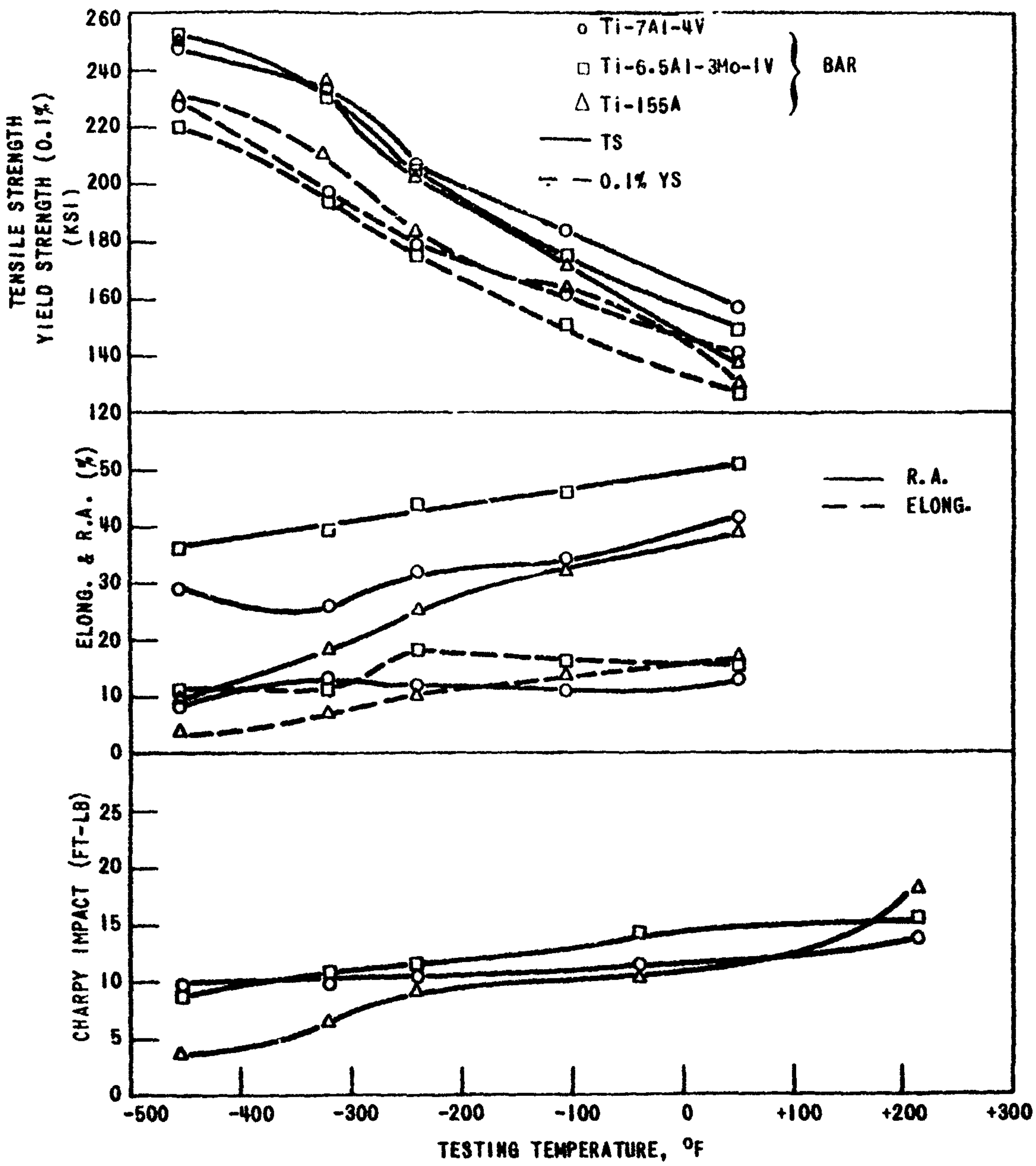
NOTE: AT -320 F SPECIMEN BROKE BEFORE DESIRED OFFSET (0.1%) WAS REACHED.

FIGURE A-5



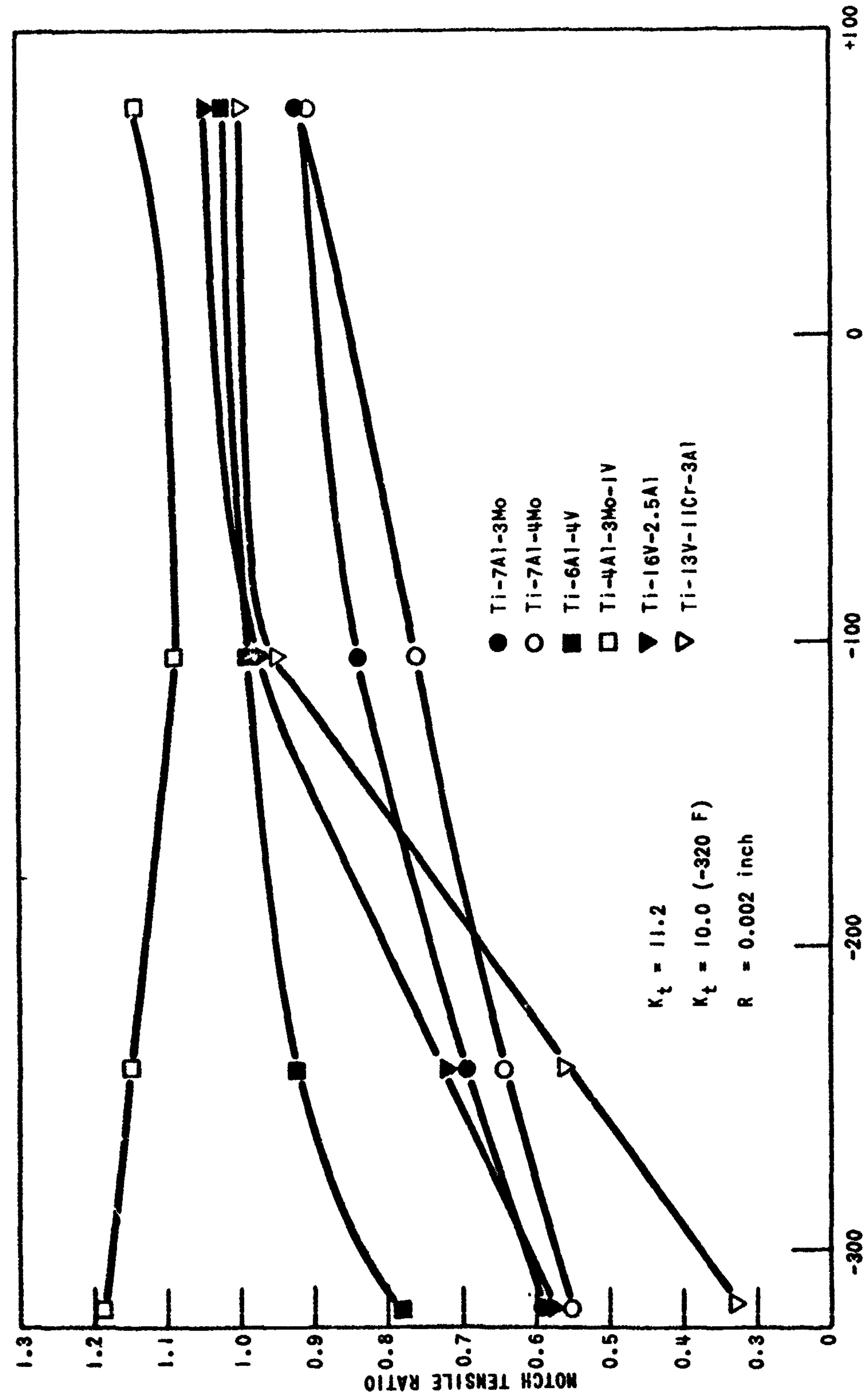
LOW TEMPERATURE MECHANICAL PROPERTIES OF Ti-13V-11Cr-3Al ALLOY

FIGURE A-6



LOW TEMPERATURE MECHANICAL PROPERTIES OF TITANIUM ALLOYS

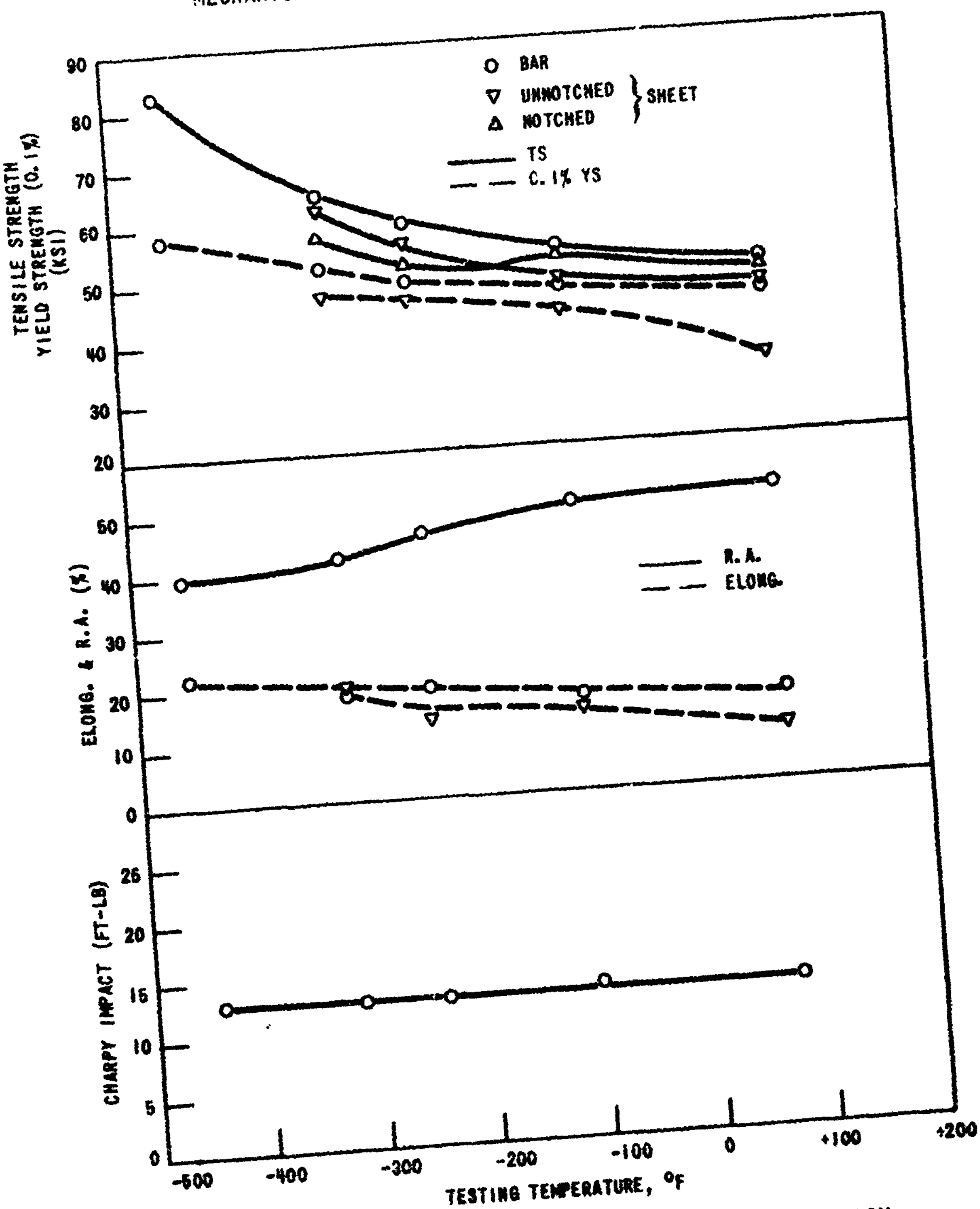
FIGURE A-7



EFFECT OF TESTING TEMPERATURE ON NOTCH TENSILE RATIO OF TITANIUM ALLOYS

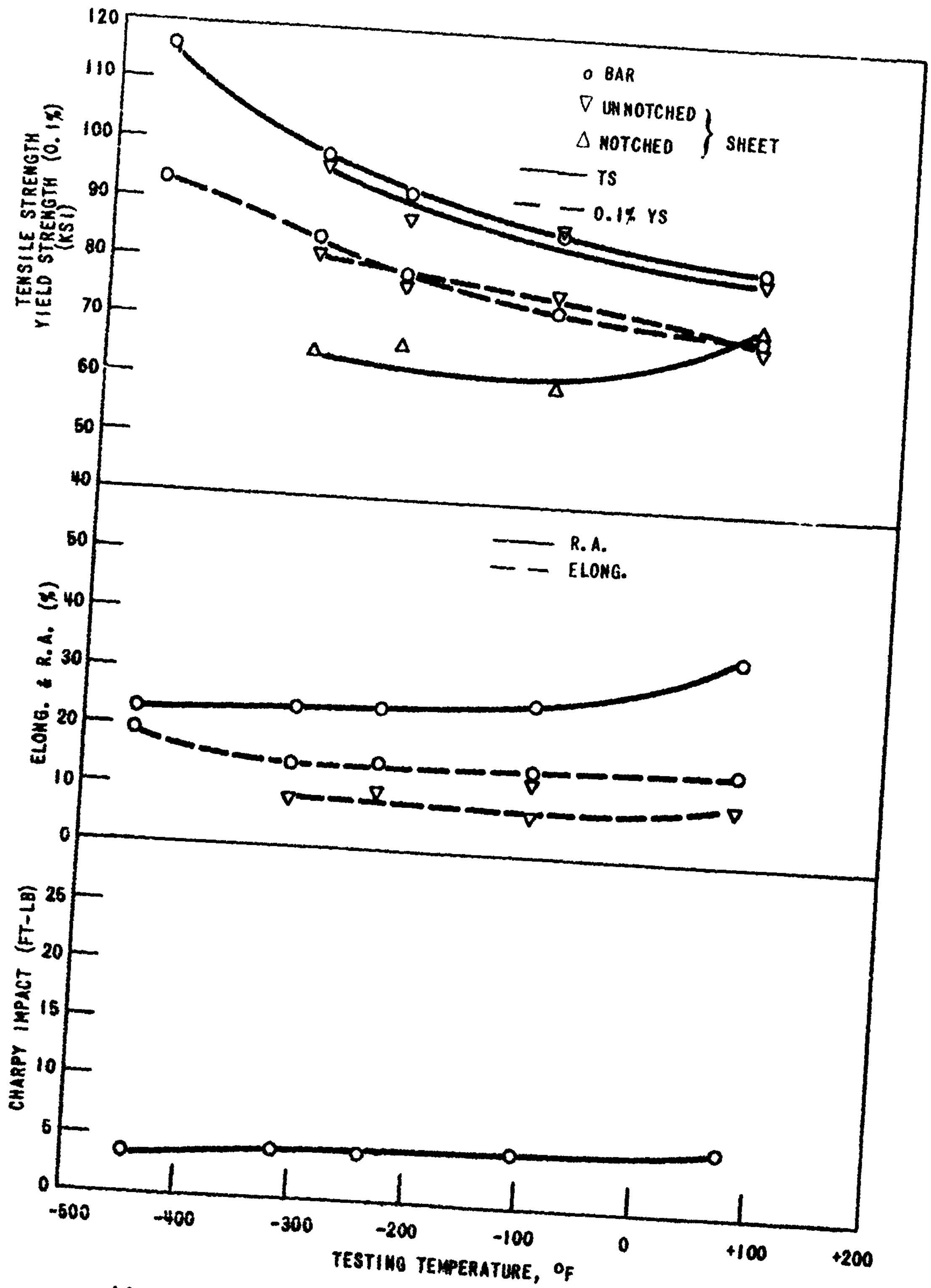
FIGURE A-8

MECHANICAL PROPERTY CURVES FOR ALUMINUM ALLOYS



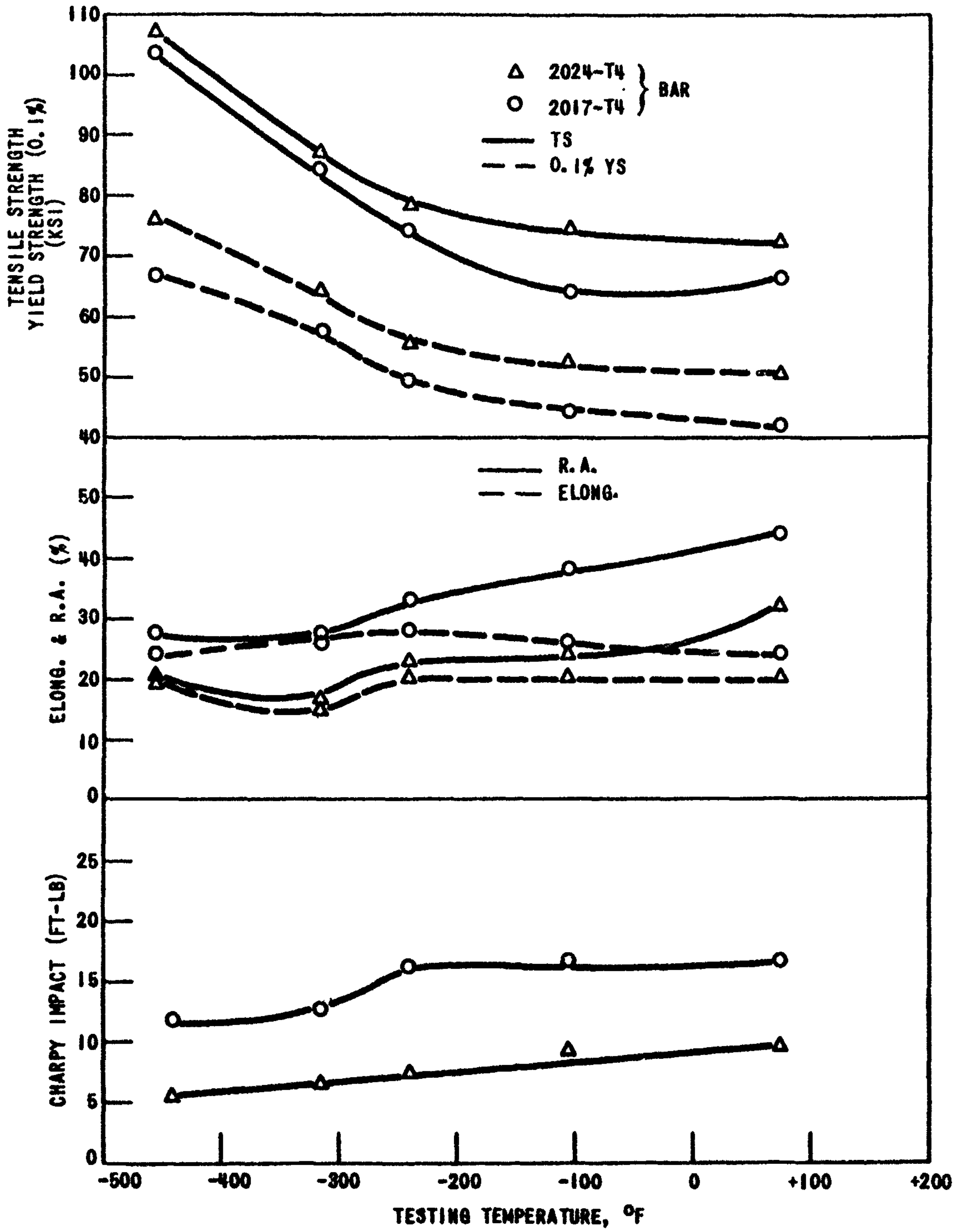
LOW TEMPERATURE MECHANICAL PROPERTIES OF 6061-T6 ALLOY

FIGURE B-1



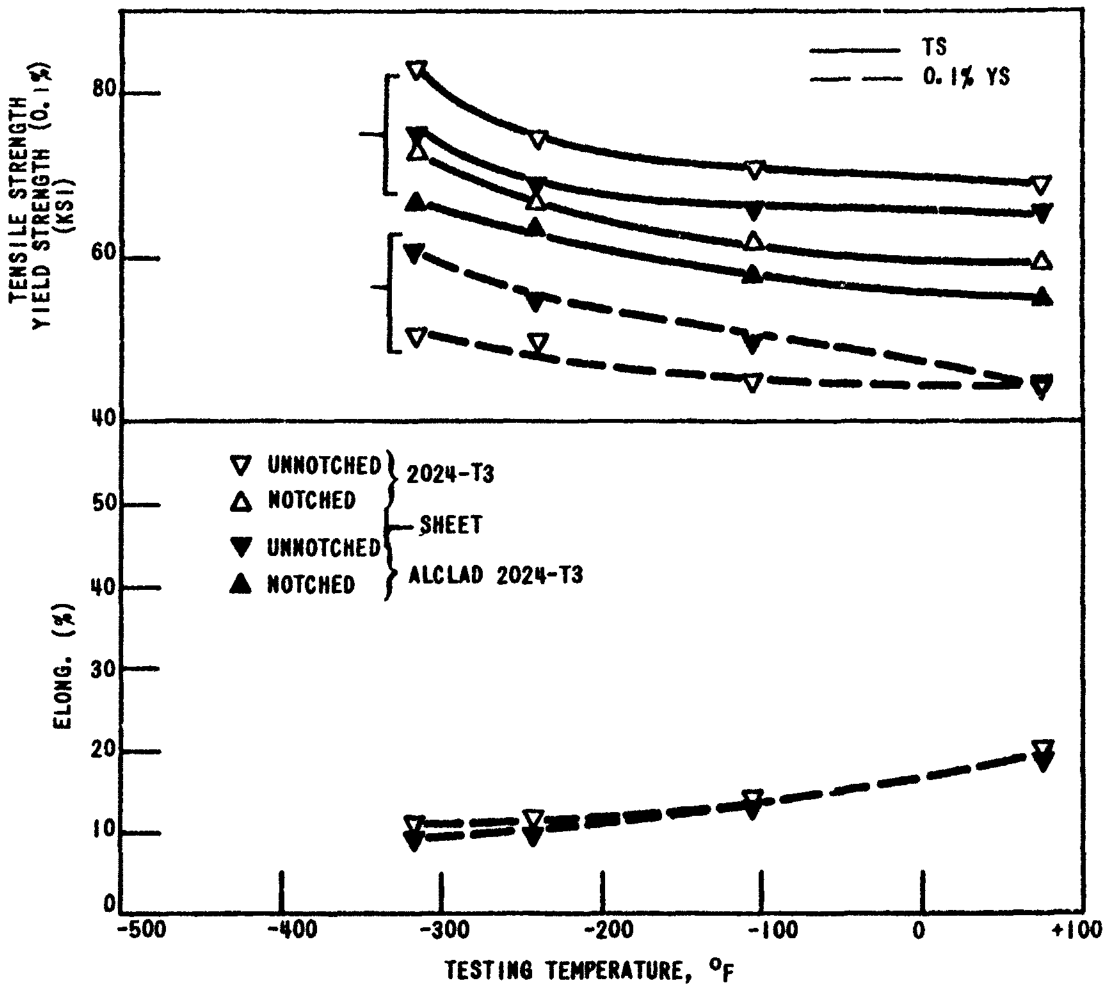
LOW TEMPERATURE MECHANICAL PROPERTIES OF 7075-T6 ALLOY

FIGURE B-2



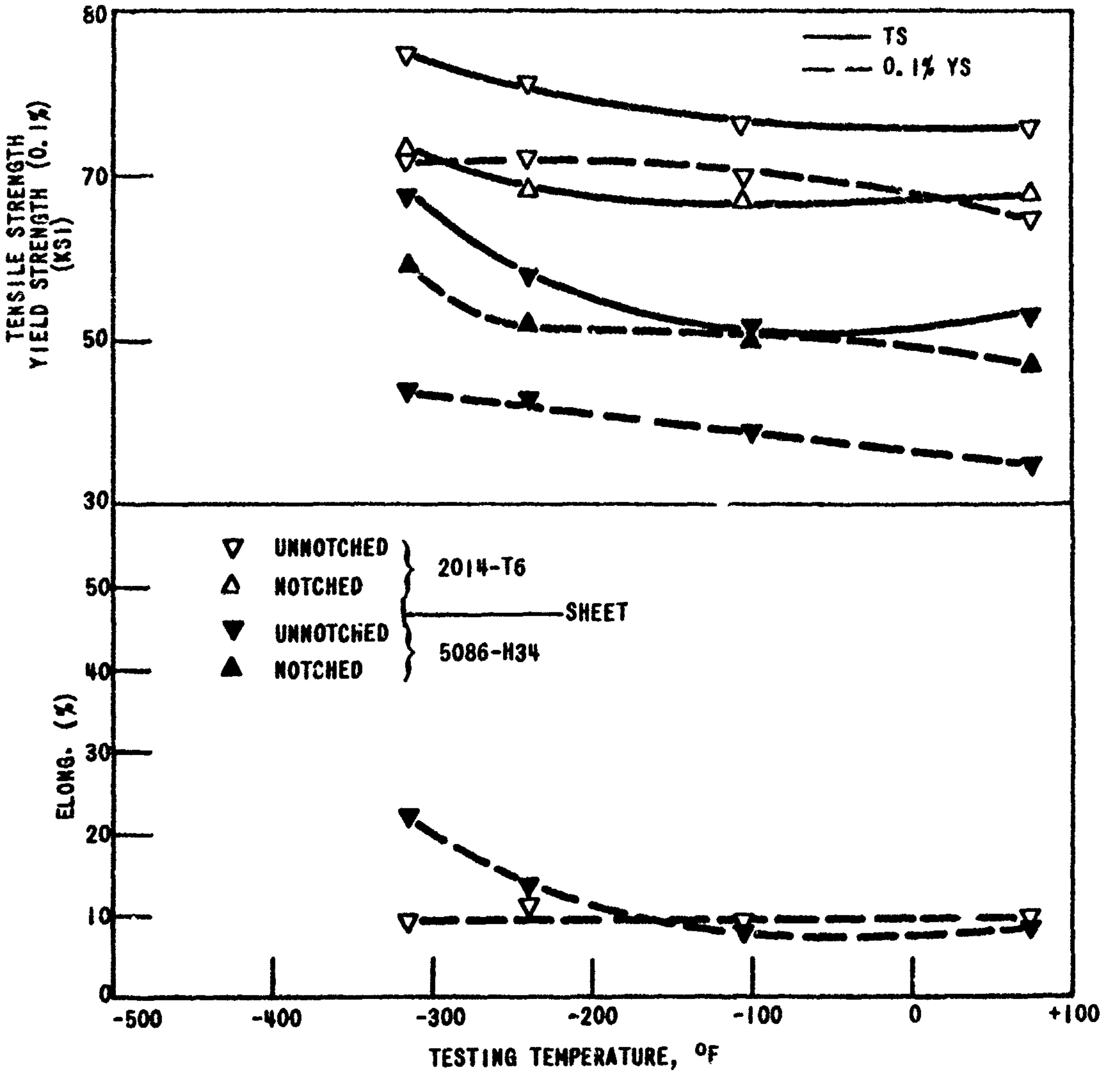
LOW TEMPERATURE MECHANICAL PROPERTIES OF ALUMINUM ALLOYS

FIGURE B-3



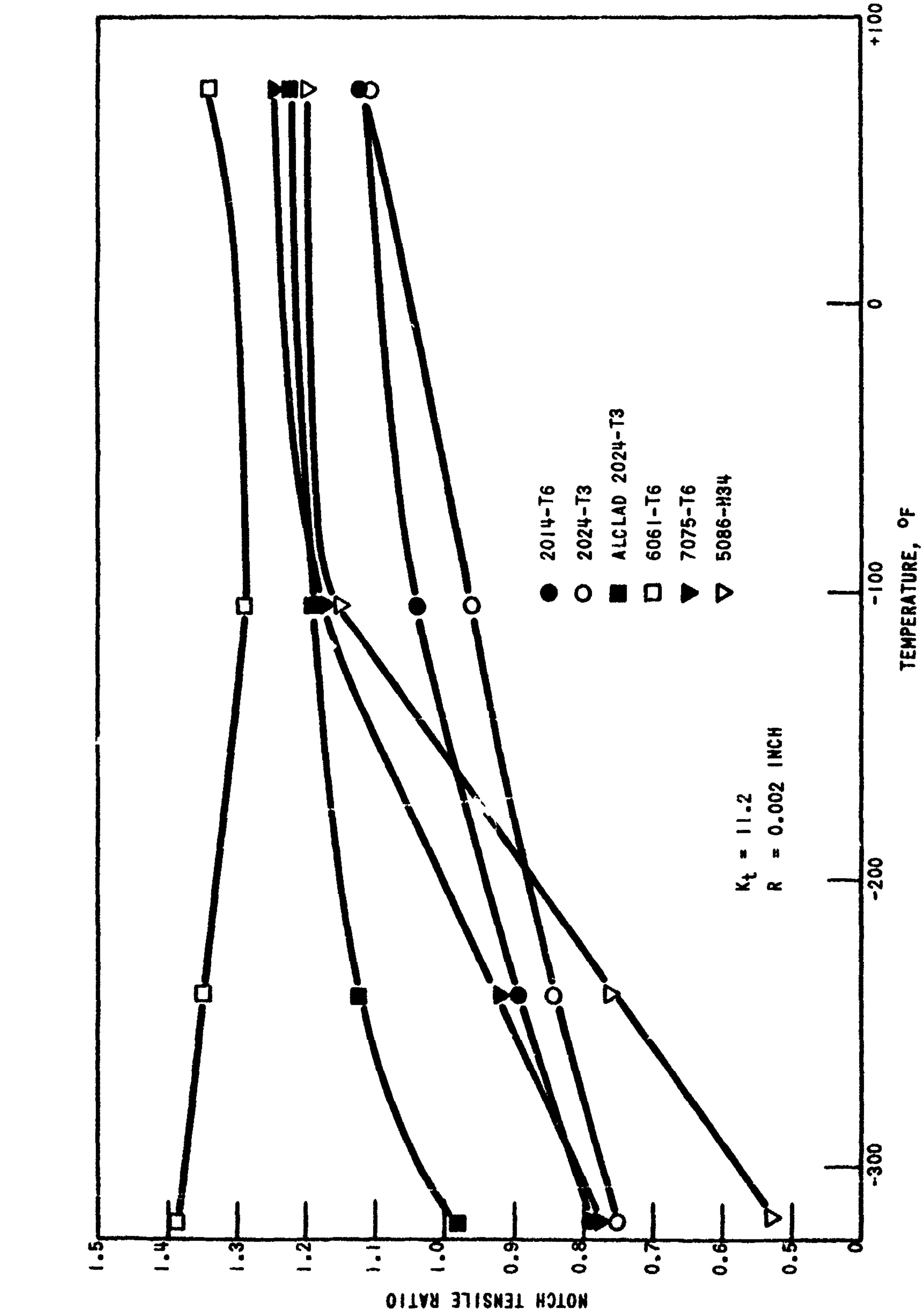
LOW TEMPERATURE MECHANICAL PROPERTIES ON ALUMINUM ALLOYS

FIGURE B-4



LOW TEMPERATURE MECHANICAL PROPERTIES OF ALUMINUM ALLOYS

FIGURE B-5



EFFECT OF TESTING TEMPERATURE ON NOTCH TENSILE RATIO OF ALUMINUM ALLOYS

FIGURE B-6

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The results of this investigation indicate that a majority of the titanium and nearly all the aluminum alloys are acceptable for applications in a cryogenic environment.

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